

A Reconnaissance Geophysical Survey of the Kawartha Lakes and Lake Simcoe, Ontario

Levé géophysique de reconnaissance des lacs Kawartha et du lac Simcoe, Ontario

Eine geophysikalische Erkundung und Vermessung der Kawarthaseen und des Simcoesees, Ontario

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La néotectonique de la région des Grands Lacs
Neotectonics of the Great Lakes area

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Résumé de l'article

Le levé a été mené afin de déceler les éléments néotectoniques et d'évaluer leur importance géologique. Des profils de sismique réflexion de haute résolution ont servi à déterminer les couches et les structures sédimentaires tardi- et postglaciaires ainsi que l'interface sédiment-roche en place dans les lacs Kawartha et le lac Simcoe. Les résultats montrent qu'il y a deux séquences sismostratigraphiques communes dans la couverture de dépôts meubles. L'unité inférieure présente une configuration de réflexion parallèle avec de fortes amplitudes, alors que l'unité supérieure est transparente du point de vue acoustique et recouvre l'unité inférieure parfois en concordance, parfois en discordance. L'épaisseur des deux unités varie à l'intérieur d'un lac et d'un lac à l'autre. Les profils caractéristiques des surfaces précambriennes sont ondulés, tandis que ceux des surfaces paléozoïques sont plats. En un site du Lower Buckhorn Lake, la surface de roches basculées est peut être faillée, mais on n'a observé aucune perturbation dans les sédiments glaciaires sus-jacents. Dans la partie ouest du lac Simcoe et la Kempenfelt Bay, on a observé des glissements dans des formes ressemblant à des grabens. On a également relevé une forme diapirique dans le lac Simcoe. On croit que ces perturbations sont probablement le résultat de la fonte de blocs glaciaires et de la migration de fluides. À ce stade des recherches, on ne peut toutefois pas écarter une origine tectonique. On devra effectuer un levé géophysique systématique afin de cartographier toutes les formes et de déterminer leur origine néotectonique ou glaciotectonique.

A RECONNAISSANCE GEOPHYSICAL SURVEY OF THE KAWARTHA LAKES AND LAKE SIMCOE, ONTARIO*

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ABSTRACT A marine geophysical survey program has been conducted in lakes of southern Ontario. The survey was designed to detect neotectonic features, if they exist, and to evaluate their geological importance. High-resolution single- and multichannel seismic reflection profiling were used to delineate late- and post-glacial sedimentary strata and structures, as well as the sediment/bedrock interface, in the Kawartha Lakes and Lake Simcoe. Results show that two seismostratigraphic sequences are common within the unconsolidated overburden. The lower unit exhibits a parallel reflection configuration having strong reflection amplitudes, whereas the upper unit is acoustically transparent and overlies the lower unit conformably in some places and unconformably in others. Both units vary in thickness within lakes and from lake to lake. Typical subbottom profiles of Precambrian rock surfaces are rolling; those of Paleozoic rock surfaces are smooth. At one location in Lower Buckhorn Lake, tilted rock surfaces may be faulted but disturbance of overlying glaciogenic sediments was not observed. In western Lake Simcoe and Kempenfelt Bay, slumping into graben-like features was observed. Also in Lake Simcoe, a diapiric feature was documented. It is speculated that these disturbances most likely result from glacier ice block melting and fluid migration. A tectonic origin, however, cannot be discounted at this stage of investigation. Additional systematic marine geophysical surveys are required in the future to map features in detail to determine whether they are of neotectonic or glaciotectonic origin.

RÉSUMÉ *Levé géophysique de reconnaissance des lacs Kawartha et du lac Simcoe, Ontario.* Le levé a été mené afin de déceler les éléments néotectoniques et d'évaluer leur importance géologique. Des profils de sismique réflexion de haute résolution ont servi à déterminer les couches et les structures sédimentaires tardi- et postglaciaires ainsi que l'interface sédiment-roche en place dans les lacs Kawartha et le lac Simcoe. Les résultats montrent qu'il y a deux séquences seismostratigraphiques communes dans la couverture de dépôts meubles. L'unité inférieure présente une configuration de réflexion parallèle avec de fortes amplitudes, alors que l'unité supérieure est transparente du point de vue acoustique et recouvre l'unité inférieure parfois en concordance, parfois en discordance. L'épaisseur des deux unités varie à l'intérieur d'un lac et d'un lac à l'autre. Les profils caractéristiques des surfaces précambriennes sont ondulés, tandis que ceux des surfaces paléozoïques sont plats. En un site du Lower Buckhorn Lake, la surface de roches basculées est peut être faillée, mais on n'a observé aucune perturbation dans les sédiments glaciaires sus-jacents. Dans la partie ouest du lac Simcoe et la Kempenfelt Bay, on a observé des glissements dans des formes ressemblant à des grabens. On a également relevé une forme diapirique dans le lac Simcoe. On croit que ces perturbations sont probablement le résultat de la fonte de blocs glaciaires et de la migration de fluides. À ce stade des recherches, on ne peut toutefois pas écarter une origine tectonique. On devra effectuer un levé géophysique systématique afin de cartographier toutes les formes et de déterminer leur origine néotectonique ou glaciotectonique.

ZUSAMMENFASSUNG *Eine geophysikalische Erkundung und Vermessung der Kawarthaseen und des Simcoeesees, Ontario.* Ein marines geophysikalisches Vermessungsprogramm wurde in Seen von Südontario durchgeführt. Die Vermessung war angelegt, um eventuell vorhandene neotektonische Elemente zu entdecken und ihre geologische Bedeutung zu bestimmen. Seismische Reflexionsprofile einfacher oder mehrfacher Frequenz mit hoher Auflösung wurden benutzt, um die spät- und postglazialen Sedimentschichten und -strukturen sowie das Interface Sediment/anstehendes Gestein in den Kawarthaseen und dem Simcoeese zu bestimmen. Die Ergebnisse zeigen, daß es zwei gemeinsame seismostratigraphische Sequenzen innerhalb der nicht verfestigten Überlastung gibt. Die untere Einheit zeigt eine Parallel-Reflektorstruktur mit starken Reflexionsweiten, wohingegen die höhere Einheit akustisch transparent ist und die untere Einheit an einigen Stellen gleichgelagert und an anderen ungleich gelagert bedeckt. Die Dicke der beiden Einheiten variiert innerhalb der Seen und von einem See zum anderen. Die typischen Unterbauprofile der präkambrischen Felsoberflächen sind wellig, die der paläozoischen Felsoberflächen glatt. An einer Stelle im unteren Buckhornsee sind die gekippten Felsoberflächen vielleicht verworfen, doch beobachtet man keine Störung der darübergelagerten glaziogenen Sedimente. Im westlichen Simcoeese und der Kempenfelt Bay hat man Abrutschungen in grabenartige Formen festgestellt. Außerdem ist im Simcoeese eine diapire Form dokumentiert. Man vermutet, daß diese Störungen höchstwahrscheinlich auf das Schmelzen von Gletschereisblöcken und flüssige Wanderungen zurückzuführen sind. In dessen kann in diesem Stadium der Forschung ein tektonischer Ursprung nicht ausgeschlossen werden.

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INTRODUCTION

Over the last decade, there has been increased concern about the identification and documentation of neotectonic activity and related geological features in southern Ontario, one of the most populated areas of Canada (Wallach and Mohajer, 1990; Mohajer *et al.*, 1992). Although both subaerial and subaqueous geological evidence of neotectonism from several sites in eastern Canada have been reported (Adams, 1982a, 1982b, 1989; McFall and Allam, 1991; Shilts, 1984; Shilts *et al.*, 1989; Shilts *et al.*, 1992; Thomas *et al.*, 1989), systematic geophysical mapping of neotectonic features in southern Ontario has been lacking.

The lakes of southern Ontario contain a record of sedimentation in late-glacial (since about 15-12 ka) and postglacial time. Because of their clayey or organic composition and high water content, lacustrine sediments are highly deformable and are susceptible to disturbance during earthquakes, and these features may be preserved in the sediments (Doig, 1991). Therefore, the lakes of southern Ontario should be potential sites for the detection and mapping of neotectonic features resulting from past seismic events. This paleoseismic geological record can be used to enhance the evaluation of the nature of future potential seismic activity in southern Ontario.

The Geological Survey of Canada has undertaken a marine geophysical survey program to address the geological history and neotectonic record of the sediments in southern Ontario lakes near metropolitan Toronto. This area encompasses not only a high population density, but also a

highly developed transportation corridor, industrial base and power generation and distribution system. A regional marine seismic survey has been undertaken in western Lake Ontario (Lewis *et al.*, 1992). The objective of this paper is to report results from a reconnaissance marine seismic investigation of the sediments and bedrock beneath the Kawartha Lakes and Lake Simcoe in the region north of metropolitan Toronto.

STUDY AREA

PHYSIOGRAPHIC SETTING

The study area straddles the boundary of the Laurentian Highlands and West St. Lawrence Lowland between Georgian Bay and Lake Ontario (Fig. 1) (Bostock, 1970). The Kawartha Lakes extend 70 km from Balsam Lake (256 m asl) in the west to Stony Lake (234 m asl) in the east; they drain southeastward to Lake Ontario (74 m asl). These lake basins are in regions mapped as limestone plain, till plain and till moraine (Barnett *et al.*, 1991; Karrow, 1989). Lake Simcoe (219 m asl) lies to the west of the Kawartha Lakes and extends 45 km both west to east and south to north; it drains northward to Georgian Bay (176 m asl). Lake Simcoe is surrounded by clay plain and sand plain of glacial Lake Algonquin (Chapman and Putnam, 1984).

BEDROCK GEOLOGY

The eastern Kawartha Lakes lie just to the south of, and partially straddle, the contact between Middle Ordovician limestone to the south and Precambrian (Grenville) metasedimentary and gneissic rocks to the north (Fig. 1). Farther west in the study area, basement outcrop is Middle and Late Ordovician limestone. The Precambrian bedrock surface is

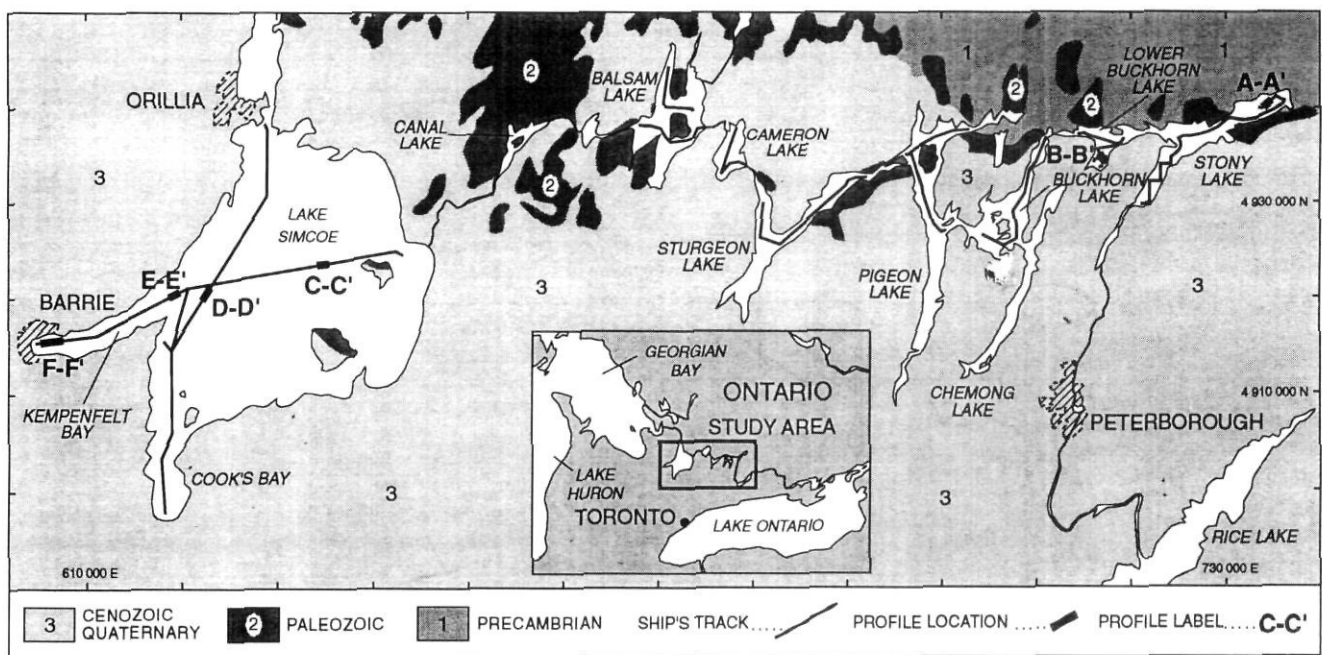


FIGURE 1. Location map of the Kawartha Lakes and Lake Simcoe in southern Ontario. Geology is simplified from Barnett *et al.* (1991). Ship's track is indicated by solid lines. Seismic reflection profile locations are highlighted by thick lines.

Carte de localisation des lacs Kawartha et du lac Simcoe, au sud de l'Ontario. La géologie est généralisée à partir de Barnett *et al.* (1991). Les itinéraires du navire sont donnés par le trait continu. Les sites des profils de sismique réflexion sont soulignés par les traits gras.

highly irregular (relief of 15-25 m), whereas the surface of the younger Ordovician carbonate rock strata is much more regular. These Ordovician rocks dip gently on a regional scale at 4-6 m/km southwesterly (Johnson *et al.*, 1992). Local dips of Paleozoic rocks are greater where they are draped over Precambrian relief. The Paleozoic rock section thickens downdip towards the Appalachian and Michigan Basins south of Lake Ontario and west of Lake Huron respectively (Liberty, 1969; Johnson *et al.*, 1992; Sanford, 1992).

SURFICIAL GEOLOGY

The Kewartha Lakes and Lake Simcoe area was glaciated by the Laurentide Ice Sheet with predominantly south to southwest ice flow (Chapman and Putnam, 1984; Karrow, 1989; Barnett, 1992). Subaerially exposed glaciogenic deposits in the study area are Wisconsinian in age and are undifferentiated tills with minor exposures of glaciofluvial ice-contact and outwash deposits (gravel and sand) and glaciolacustrine deposits (silt and clay, sand) (Deane, 1950; Gravenor, 1957; Barnett *et al.*, 1991). These deposits cover bedrock in the western Lake Simcoe area, but form a relatively thin to discontinuous veneer over bedrock in the Kewartha Lakes and eastern Lake Simcoe areas.

BATHYMETRY

Bathymetric data reveal major contrasts within the geomorphology of the Kewartha Lakes and Lake Simcoe. The floors of Stony, Lower Buckhorn and, to a lesser degree, Cameron and Balsam Lakes exhibit an irregular bathymetry and these lakes contain numerous islands (Canadian Hydrographic Service, 1985a, 1985c). Water depths generally range from 9-12 m but, in some locations, exceed 30 m. In contrast, Buckhorn, Pigeon and Sturgeon Lakes and Lake Simcoe have smoother, more regular lake floors and contain few islands (Canadian Hydrographic Service 1985b, 1985c, 1987). The majority of the Lake Simcoe lake floor is 18-30 m in depth. Two prominent bays on Lake Simcoe were surveyed during this study: Kempenfelt Bay is a deep (>30 m) NE-SW trending bay on the west shore of the lake and Cook's Bay (~15 m deep) extends N-S on the south side of the lake (Fig. 1).

METHODS

SURVEY VESSEL

The marine geophysical survey was conducted aboard the *MV J. Ross Mackay*, a 12 m, 15 ton aluminum hull research vessel. Its draft of 0.75 m makes the vessel an ideal platform from which to conduct geophysical surveys in shallow inland waters.

NAVIGATION

Electronic navigation used throughout the survey was the satellite-based Global Positioning System (GPS). In its present form, GPS can obtain position fixes at a rate of one per second with an accuracy of 25 m (circular probable error, or CEP). The U.S. Department of Defence purposely degrades the accuracy of the system to 125 m (CEP) by initiating selective satellite availability at any time (King *et al.*, 1987).

Accurate positioning was confirmed during the course of the survey by the successful reoccupation of survey tracks over distinct geological features. The navigation data were recorded each minute and stored in the GPS instrument (Trimble NavTracXL). The data were transferred daily to portable computer and the ship's track was plotted.

SINGLE-CHANNEL SEISMIC SYSTEM

A high-resolution single channel seismic reflection system was used to obtain detailed images of the Quaternary section. The system consisted of an ORE Geopulse power supply (300 joules) connected to a Huntex 4425 boomer mounted under a surface-towed surfboard. The receiver was an IKB Seistec line-in-cone array towed near surface in a catamaran. The system operated over a frequency range of 1800 Hz to 6-8 kHz and was fired at a 1 s interval with a survey speed of 2 knots thereby sampling the subsurface each metre horizontally. Data were displayed on two EPC 1600 graphic recorders, one with a 100 ms sweep and one with a 50 ms sweep, and were recorded with a Hewlett Packard 3968 8-channel analogue tape recorder at 3.75 i/s (9.5 cm/s). Examples of data recorded with this system are shown in Figures 2-7. The vertical resolution of the Seistec system ranged from 10-20 cm. The high degree of both vertical and horizontal resolution, combined with a depth penetration of almost 40 m in some instances, made the Seistec system an excellent tool to delineate Quaternary sedimentary strata and structures throughout the survey.

MULTI-CHANNEL SEISMIC SYSTEM

A high-resolution multi-channel seismic reflection system was used in Lake Simcoe to obtain images of the sediment/bedrock interface. The seismic energy source was a 10 in³ (164 cm³) Bolt 600B airgun fired at 1800 psi at a 15 s rate at a depth of 1.5 m. At the survey speed of 2 knots, airgun shots were spaced 15.4 m horizontally. The receiver was a refraction/reflection 12-channel eel developed by the Geological Survey of Canada (Good *et al.*, 1984). The active portion of the eel consists of 12 groups of hydrophones with 7.5 m between groups. Each group is composed of 2 elements (Benthos AQ-16 type) spaced at 30 cm. The hydrophone array is housed inside a neutrally-buoyant oil-filled hose having an outer diameter of 3.2 cm. The layback from the GPS antenna was 21.5 m to the airgun, and 29 m to group 1 on the eel.

The seismic reflection data were recorded using an EG&G ES2401 engineering seismograph. The record length was 400 ms using a 0.2 ms sample rate. Frequency spectra of shot records showed a frequency content of 400-600 Hz. The data were stored on hard disc on the seismograph and processed each day. Examples of data recorded with this system are shown in Figures 7 and 9. The vertical resolution of this system was 1.5-2.5 m with a depth penetration of almost 100 m through unconsolidated sediments. The multi-channel seismic reflection system provided details of the sediment/bedrock interface which were beyond the capability of the Seistec system.

In addition to the two seismic systems described above, shallow high-resolution seismic data were recorded using a

Raytheon RTT 1000 subbottom profiler with a frequency of 7 kHz at a rate of 534 soundings per minute. A vertical resolution of about a metre was obtained with this profiler but its depth penetration was only a few metres. Sidescan sonar data were also collected using an EG&G 260 sidescan sonar. The sidescan images provided a plan view of the lakefloor morphology and information on the type and distribution of sediment.

The ship's track in the Kewartha Lakes and Lake Simcoe is shown in Figure 1. Navigable waters amenable to geophysical surveys in the Kewartha Lakes are restricted in aerial extent by islands, shoals, shallow water and, in the summer months, extensive weed beds. Nonetheless, channels are maintained throughout the lakes by Environment Canada Parks Service and these channels served as the main geophysical survey routes. Although the limited seismic coverage shown in Figure 1 does not allow detailed mapping of the distribution of lakebed features, it does provide evidence for general relationships among morphological features and sediment structure.

DESCRIPTION AND INTERPRETATION OF SEISMIC PROFILES

The following descriptions of seismostratigraphy evident in the seismic reflection profiles employ the terminology of Mitchum, Vail and Sangree (1977) and Mitchum, Vail and Thompson (1977). On all the seismic profiles, both two-way reflection time and depth scales are shown. An approximate sediment velocity of 1500 m/s was used to calculate the depth scales.

When interpreting seismic reflection profiles for evidence of neotectonism in unconsolidated lacustrine sediments, it is important to keep in mind the various ways in which these sediments may deform. Shilts and Clague (1992) outlined three modes of deformation:

1. Sediments may fail and move downslope under the influence of gravity. The processes by which this downslope movement may occur are creep, sliding, slumping, or flow.
2. Sediments may become faulted or folded due to tectonism (coseismic or aseismic), glacial processes (e.g. glacier over-riding or sediment collapse over melting, buried glacier ice), differential compaction, or sudden loading or unloading resulting from mass transport processes.
3. Sediments may undergo *in situ* liquefaction. Buried, water-saturated sands and silts, subject to rapid sediment loading or shaking during earthquakes, may liquefy. Water expulsion and diapirism may accompany liquefaction. Similarly, water released from melting blocks of glacier ice buried by late-glacial sediments may cause localized liquefaction and diapirism.

Shilts and Clague (1992) pointed out that faults in glacio-lacustrine sediments, produced by tectonically-induced movements in bedrock beneath lakes, will be difficult to differentiate from faults of glacial or glaciotectionic origin. A neotectonic origin for a fault is possible if the fault plane extends from bedrock into, and through, overlying postglacial sediments. If displacement occurs along the fault plane, both in

the postglacial sediments and in the underlying bedrock, tectonic reactivation or origin is certain. It is important to recognize that sometimes sharp, minor escarpments in underlying bedrock, particularly in Paleozoic, flat-lying carbonates, give rise to fault-like displacements in sediments (Shilts and Clague, Fig. 9, 1992).

PRECAMBRIAN LAKEFLOOR: STONY LAKE

Figure 2 shows seismic profile A-A' from eastern Stony Lake (Fig. 1). The north shore and islands of Stony Lake are almost all Precambrian outcrop (rocks of the Grenville Central Metasedimentary Belt), whereas the south shore is Paleozoic sedimentary rock (limestone). This profile lies between islands of exposed Precambrian bedrock and the bedrock in the profile is interpreted as Precambrian. The bedrock surface is irregular with vertical relief over 10 m. Sediment thickness in bedrock basins reaches 7 m and is probably greater, but is obscured by the presence of gas. Unit A lies on bedrock and is characterized by parallel internal reflectors with strong amplitude. In contrast, the overlying Unit B is characterized by weak internal reflections; at some locations Unit B is almost acoustically transparent with a weakly-reflective parallel to convergent configuration. Unit B overlies Unit A unconformably. Unit B selectively infills the basin lows in Unit A and onlaps the basin margins as at 1220 m along the profile in Figure 2.

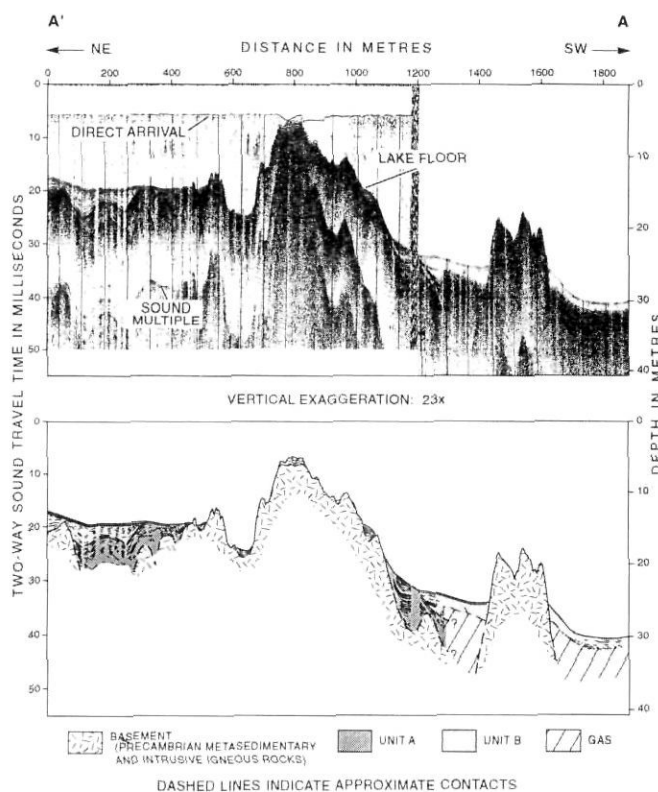


FIGURE 2. Single-channel seismic reflection profile A-A' from Stony Lake and interpretative cross section showing stratigraphic relations. See Figure 1 for location of profile.

Profil de sismique réflexion monocanal A-A' à Stony Lake, et coupe interprétative montrant les liens stratigraphiques (localisation à la fig. 1).

PALEOZOIC LAKEFLOOR: LOWER BUCKHORN LAKE

Seismic reflection profile B-B' (Fig. 3) is located in Deer Bay on the south shore of Lower Buckhorn Lake (Fig. 1). Deer Bay is floored by upper Middle Ordovician sedimentary rocks (Sanford, 1992). The eastern shore of the bay is marked by a cliff of sedimentary rocks reaching 10 m above lake level. Penetration of the seismic energy into the sediments in Deer Bay was severely reduced by gas. The upper surface of gas-charged sediments often produced a high-amplitude bottom-simulating reflector (Fig. 3, 0-250 m along profile). Only on the east side of the bay, adjacent to the cliff, was any appreciable seismic energy penetration achieved. Basement on the seismic profile in Figure 3 is interpreted as Paleozoic sedimentary rocks. The irregular basement relief could be related to faulting or to erosion along faults; faults have been mapped in bedrock to the north of Lower Buckhorn Lake (J.L. Wallach, pers. comm., 1992).

Unit A reaches a measurable thickness of about 10 m, but its maximum thickness is obscured by gas. The unit drapes both bedrock highs and the reflection configuration within Unit A is parallel to subparallel (Fig. 3). In the centre of the section, reflectors show a broken, almost chaotic, configuration suggesting either sediment slumping off the basement high during deposition of Unit A or post-depositional disturbance of Unit A but before deposition of the overlying Unit B. The top of Unit A is highly reflective (350-520 m along Profile BB'), suggesting a coarse sediment. In some locations (600-

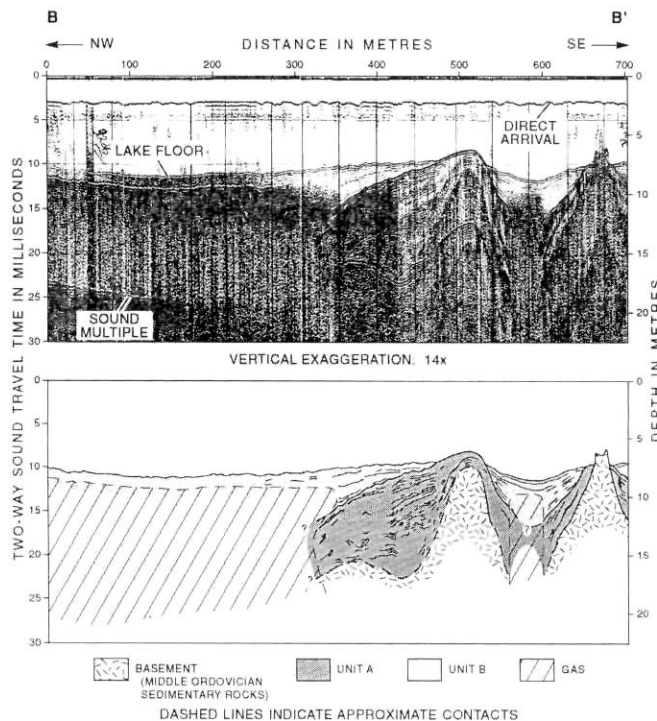


FIGURE 3. Single-channel seismic reflection profile B-B' from Lower Buckhorn Lake and interpretative cross section showing stratigraphic relations. See Figure 1 for location of profile.

Profil de sismique réflexion monocanal B-B', à Lower Buckhorn Lake, et coupe interprétative montrant les liens stratigraphiques (localisation à la fig. 1).

650 m), Unit A has been eroded to form an angular unconformity with Unit B.

The weak, low-amplitude, sub-parallel reflectors within Unit B onlap Unit A (400-475 m and 525-650 m along the profile) and show no evidence of slumping. Unit B is heavily charged with gas (Fig. 3), especially where the unit ponds in lows. The unit is very thin or absent on the basement highs where Unit A may be exposed, in some instances, at the lakefloor.

LAKE SIMCOE PROFILES

Profile C-C'

Seismic profile C-C' from Lake Simcoe is shown in Figure 4. This profile is from the eastern section of the lake (Fig. 1) near two islands on which Paleozoic rocks outcrop. The 10 m-high mesa-like feature on the left (east) side of the profile is interpreted as an outcrop of flat-lying Paleozoic bedrock. Horizontal internal reflectors are vaguely evident in parts of the upper portion of the outcrop and beneath Unit A. Sidescan sonar images, not shown here, show a jointing pattern characteristic of limestone. Based on the seismic and sidescan data, the stepped appearance of the upper surface of the outcrop are interpreted as edges of individual beds. Extensive outcrops of Paleozoic bedrock, showing an identical morphology, have been mapped using seismic profiling and sidescan sonar in eastern Lake Ontario off Prince Edward County (B.J. Todd, unpublished data).

Unit A is relatively thin, about 5 m in thickness, but Unit B is absent or very thin, possibly due to nondeposition or erosion near the exposed bedrock shoal.

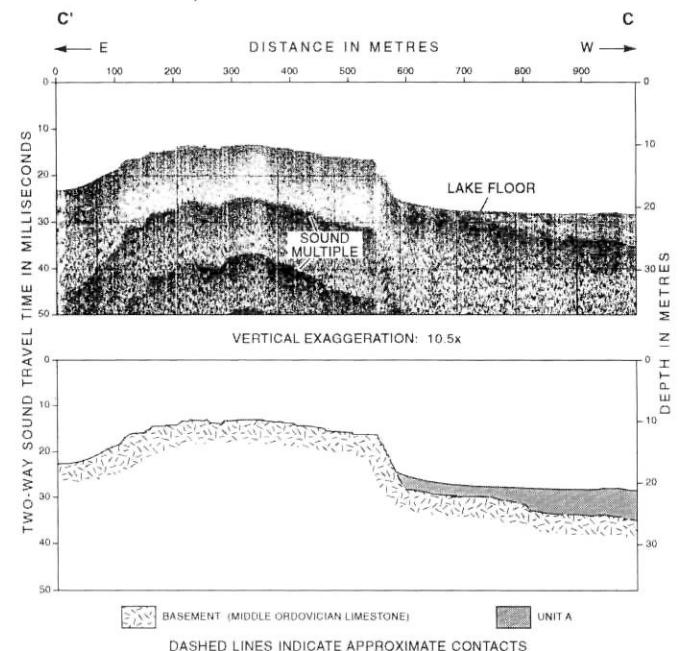


FIGURE 4. Single-channel seismic reflection profile C-C' from Lake Simcoe and interpretative cross section showing stratigraphic relations. See Figure 1 for location of profile.

Profil de sismique réflexion monocanal C-C' au lac Simcoe, et coupe interprétative montrant les liens stratigraphiques (localisation à la fig. 1).

Profile D-D'

The location of profile D-D' (Fig. 5) lies in western Lake Simcoe (Fig. 1). A trough extends from 500-800 m along the section and is flanked by highs (Fig. 5). The acoustic basement surface across the entire record is strongly reflective. Beneath the basement surface is a zone, about 10 m thick, of incoherent reflections. The presence of incoherent internal reflectors in this acoustic basement, differing from the bedrock reflection character in Figure 4, suggests that the material is a sediment, possibly till. The 15 m-high escarpment in the centre of the profile (450-550 m) has an apparent slope of 9° the northeast. Penetration of seismic energy into the basement at the foot of the slope shows no evidence of a fault trace; no reflecting surface extends into basement nor are any reflection hyperbolas, often characteristic of faults, present. This suggests that the basement morphology is a result of erosion. Alternatively, if the subacoustic basement bedrock is faulted, displacement predated the deposition of the acoustic basement sediment. A deeper penetrating seismic system is needed to test for evidence of faulting in the underlying bedrock.

Near D, from 0-100 m, Unit B unconformably overlies Unit A and the surface of Unit A is exposed at the lakelfloor on the basement high from 100 to 420 m. Here, the strata within Unit A are truncated at the lakelfloor and the surface of Unit A is interpreted as erosional. In the centre of the profile, Unit A reaches a thickness of about 8 m and is characterized by high-amplitude, subparallel reflections. Minor chaotic reflection patterns suggest some slumping occurred early in the deposition of Unit A in the trough. Here, up to 5 m of Unit B conformably overlies Unit A. The deposition of Unit B has been suppressed at the base of the rises at each side of the trough, possibly due to the acceleration of bottom currents around these obstructions causing nondeposition or lower rates of deposition. To the right (northeast), strata within Unit B (although faintly imaged) are truncated at the lakelfloor, suggesting that the upper surface of Unit B has been eroded.

Two mounds of basement sediment (till?) about 50 m wide and 2-3 m high are evident at 840 and 940 m along the profile. The upper part of Unit A with its strong parallel internal reflections thins over the eastern mound, and only the lower part of Unit A drapes the western mound at the edge of the trough, suggesting bottom currents were affecting depositional conditions during the latter part of Unit A formation.

Profile E-E'

Seismic reflection profile E-E' (Fig. 6) is located at the mouth of Kempenfelt Bay in Lake Simcoe (Fig. 1). Here the basement is not well-imaged due to the presence of gas at the base of Unit A. At least 17 m of Unit A is present, conformably overlain by up to 7 m of Unit B. In the centre of the profile is a 25 m-wide, vertical disturbance in the configuration of the parallel reflectors. Reflectors within this diapir-like feature below 47 m are not visible, possibly obliterated by gas. Corresponding reflectors on either side of the feature are offset about 2 m down to the southwest. This offset decreases with height up the section; the lakelfloor shows no indication of any offset above the feature. The uppermost part of Unit A thins on the western side of the feature suggesting, as in

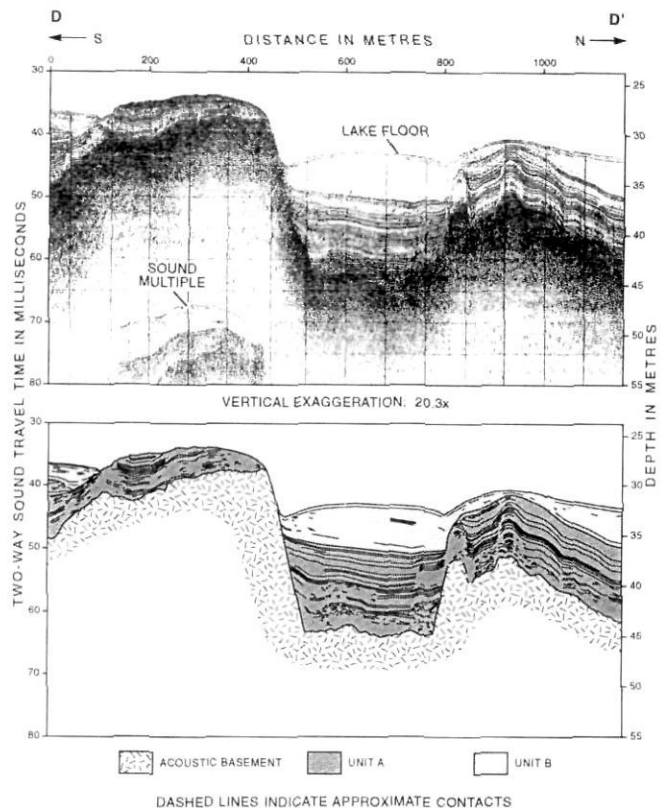


FIGURE 5. Single-channel seismic reflection profile D-D' from Lake Simcoe and interpretative cross section showing stratigraphic relations. See Figure 1 for location of profile.

Profil de sismique réflexion monocanal D-D' au lac Simcoe, et coupe interprétative montrant les liens stratigraphiques (localisation à la fig. 1).

Figure 5, that bottom currents may have influenced sediment distribution during the late stage of Unit A deposition.

This diapiric feature is also imaged by the multichannel seismic profile shown in Figure 7. The seismic energy source used to obtain these data (airgun) utilizes lower frequencies than the single channel seismic energy source (boomer). In comparison with the single channel profile (Fig. 6), fine-scale vertical resolution of the parallel-bedded units is decreased in the multichannel profile (Fig. 7) but depth penetration into basement is improved. There is no apparent vertical displacement in acoustic basement reflectors (till?) beneath the diapiric feature, although there is a small gap in their horizontal resolution.

A possible interpretation of the deformation in the sediments shown in Figures 6 and 7 is that it is glacial in origin because the deformation does not extend into the overlying modern sediments, nor does it appear to extend into the underlying basement. Dewatering of buried sediments caused by loading may be the process by which the diapiric feature formed. This can be associated with buried ice blocks (Klassen and Shiels, 1982; Shiels and Farrell, 1982). An alternate interpretation is that a fracture without displacement exists in the basement and this may have vented pressured fluids which raised the lower beds of Unit A. This event could have occurred during the deposition of Unit A and could be

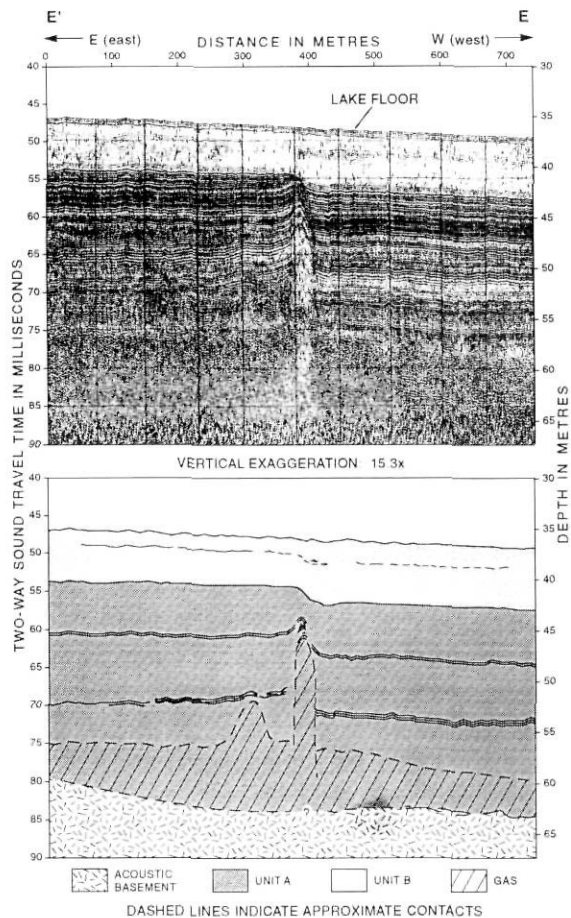


FIGURE 6. Single-channel seismic reflection profile E-E' from Lake Simcoe and interpretative cross section showing stratigraphic relations. See Figure 1 for location of profile.

Profil de sismique réflexion monocanal E-E' au lac Simcoe, et coupe interprétative montrant les liens stratigraphiques (localisation à la fig. 1).

related to tilting and stress redistribution in bedrock during rapid glacioisostatic adjustment associated with deglaciation, or to tectonic adjustment. A third possible interpretation is that faulting from bedrock, not resolved on the seismic profiles (Figs. 6,7), passes upwards into the sediments of Unit A, but pre-dates Unit B. However, this interpretation is not supported by the multichannel seismic evidence; no apparent off-set in acoustic basement exists beneath the diapiric feature (Fig. 7).

Profile F-F'

Seismic profile F-F' (Fig. 8) is located at the head of Kempenfelt Bay in Lake Simcoe (Fig. 1). The most noticeable aspect of the profile are two distinct depressions in Unit A materials, the eastern depression being 350 m wide and the western depression slightly wider. In both depressions, the upper surface of Unit A drops about 8 m below its adjacent level. Diapir-like features penetrate the bases of the depressions and there is extensive associated gas. The thickness of Unit A increases from 13 m in the west at the head of the bay (near 2700 m along the profile) to more than 25 m in the east

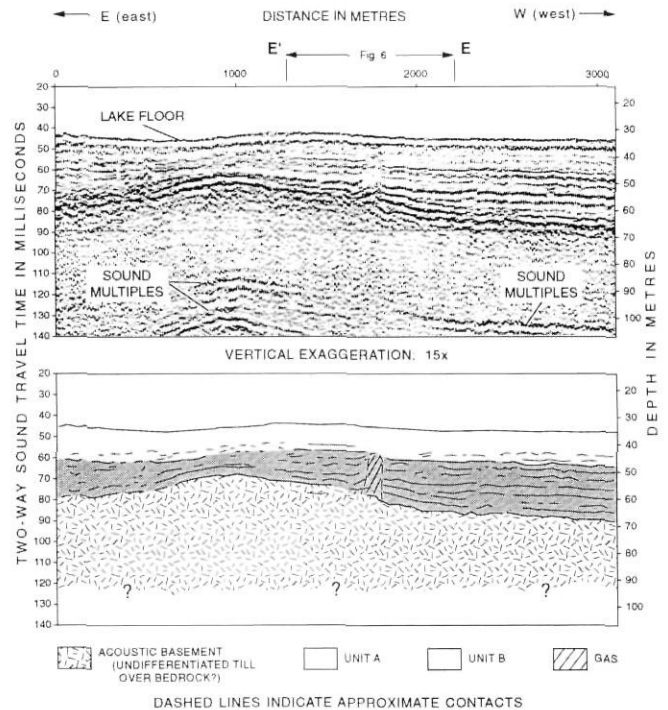


FIGURE 7. Multichannel seismic reflection profile from Lake Simcoe. Extent of single channel profile E-E' of Figure 6 is indicated.

Profil de sismique réflexion multicanal du lac Simcoe. L'étendue du profil E-E' de la figure 6 est indiquée.

(0-700 m along the profile). Unit B conformably overlies Unit A and reaches a thickness of 8 m in the depressions. Unit B is thin elsewhere and is absent from the western flank of the eastern depression, probably due to the action of bottom currents accelerated against this slope causing nondeposition.

Reflective horizons within Unit A can be traced the length of the profile (Fig. 8). Due to the vertical exaggeration of the profile, it is difficult to trace these events into the depressions. At the margins of some depressions, for example, at horizontal distances of 760 m (Fig. 8 left), 1150 m and 2600 m (Fig. 8 right), reflectors appear to terminate. In the latter case (at 2600 m), there is a clear angular unconformity within Unit A extending from 26 to 34 m depth. Slumping into the eastern depression may have occurred, indicated by the wedge of structureless material at the top of Unit A at 900 m (Fig. 8 left). Otherwise, Unit A has a draped basin fill configuration in the depressions.

Figure 9 shows the multichannel seismic profile in Kempenfelt Bay corresponding to the single-channel data in Figure 8. Reflecting horizons, lying between 10 and 40 m below the lake floor and within Unit A, can be followed horizontally beneath the depressions at 4800 m and 6250 m along the profile.

The base of recognizable, parallel reflectors lies between 80 and 100 m depth near 1000, 4000 and 7500 m along the profile (Fig. 9).

Although these depressions resemble downfaulted grabens on surface, there is yet no clear seismic evidence for

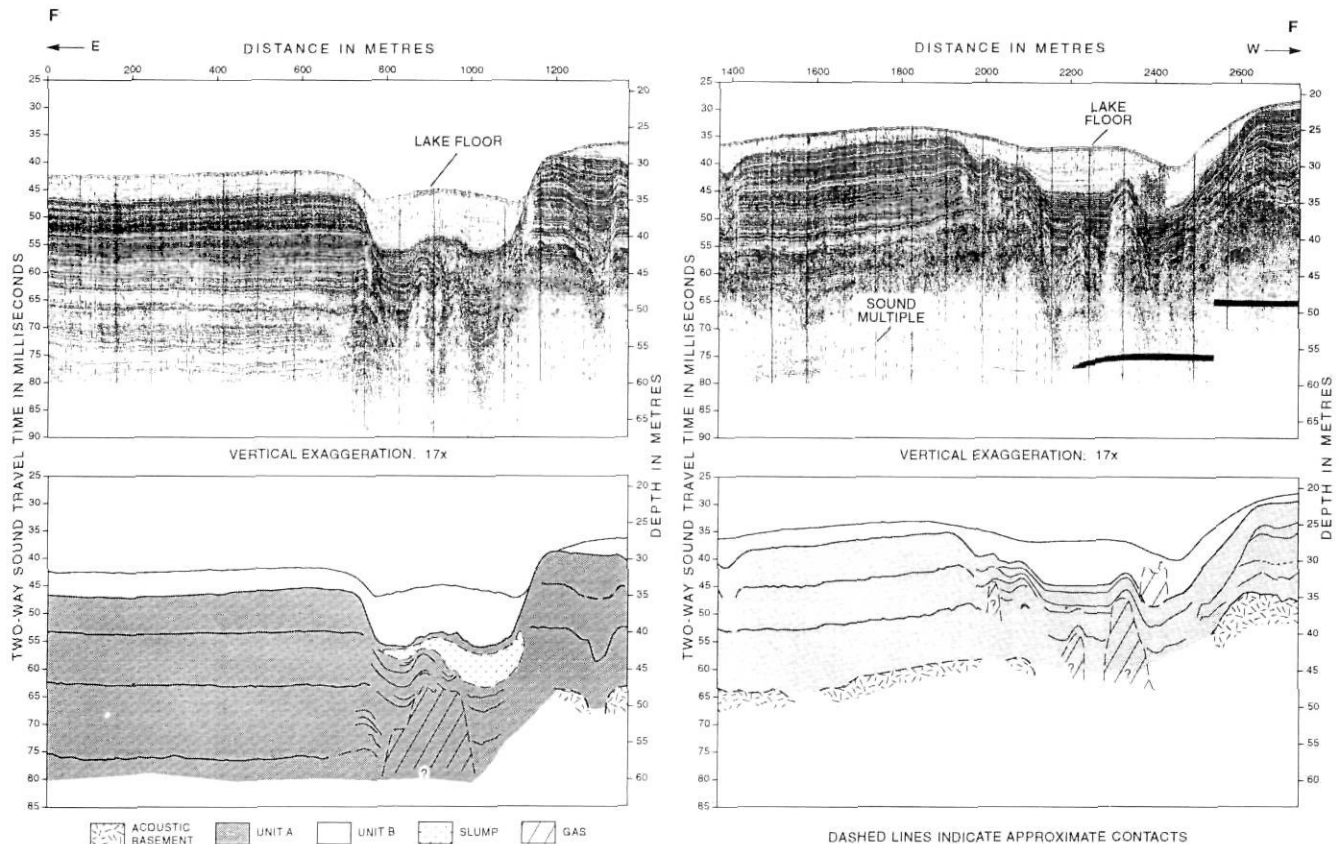


FIGURE 8. Single-channel seismic reflection profile F-F' from Lake Simcoe and interpretative cross section showing stratigraphic relations. See Figure 1 for location of profile.

faulted bedrock. However, these depressions may be associated with bedrock faults not imaged on the seismic data. Such faults could provide a pathway for upward migration of gas associated with the depressions (Fig. 8).

Based on the termination of reflectors within Unit A, on the conformal, draped nature of the sediments across the section, and on the apparent continuity of reflectors below the base of the depressions, we tentatively suggest that these depressions originated as areas beneath which blocks of buried glacial ice had melted, pending the collection of further evidence (Klassen and Shilts, 1982; Shilts, 1984; Shilts and Clague, 1992). Further processing is being applied to all Lake Simcoe single- and multichannel seismic data to improve the lateral continuity of the reflectors. Collection of additional profiles will aid in clarifying the integrity of the basement surface.

There is an indication that the sediment thickness is quite considerable in Kempenfelt Bay. This bay is on the site of a relatively broad buried bedrock valley (Deane, 1950) called Simcoe Valley by Liberty (1969). The drift-filled Simcoe Valley appears to slope westward according to bedrock contours (White and Karrow, 1971) as a tributary to the buried Laurentian Valley (Spencer, 1890) between Georgian Bay and Lake Ontario. The base of parallel reflectors in the multichannel seismic profile (Fig. 9) suggests that the valley is at least 87 m deep in the bay. Unit A, probably a late-glacial glaciolacustrine deposit, is at least 25 m thick under 4 m of Unit

Profil de sismique réflexion monocanal F-F', au lac Simcoe, et coupe interprétative montrant les liens stratigraphiques (localisation à la fig. 1).

B in 32 m water depth (e.g. Fig. 8 left, 0-600 m along profile). The presence of such a relatively youthful, narrow and deep feature within the generally drift-filled valley is enigmatic. Strategic terrestrial seismic studies around the bay combined with more marine profiling would help explain the origin and timing of these features.

DISCUSSION AND SUMMARY

A marine seismic pilot transect has been completed across the Precambrian-Paleozoic contact in central Ontario. Utilizing high-resolution boomer reflection profiling and some small airgun multichannel recording, the survey imaged selected sedimentary sections along an east to west route through the Kawartha Lakes and Lake Simcoe. In Stony Lake, the Precambrian bedrock presents a typically "rough" basement on profiles which show relief in the order of 20 m over 1 km (Fig. 2). In contrast, the gently dipping Ordovician bedrock, as imaged in an outcrop area in eastern Lake Simcoe (Fig. 4), appears as flat reflective surfaces separated by steps of 1-10 m, possibly representing limestone beds truncated by glacial quarrying, as observed onshore. An area of possible faulting of Paleozoic bedrock was interpreted in Lower Buckhorn Lake; but the faulting would have predated deposition of the overlying Unit A (Fig. 3).

Based on seismic profiles of a large number of small- to medium-size eastern Canadian lakes, Shilts and Clague

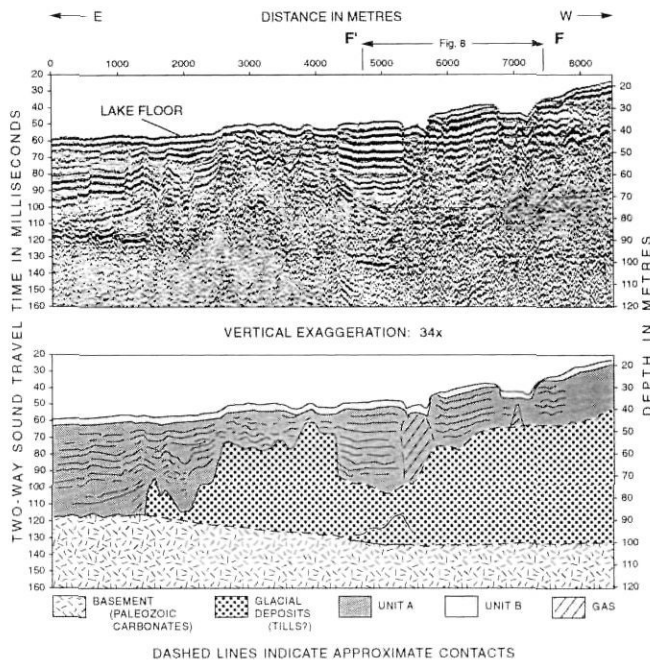


FIGURE 9. Multichannel seismic reflection profile from Lake Simcoe. Extent of single channel profile F-F' of Figure 8 is indicated.

Profil de sismique réflexion multicanal du lac Simcoe. L'étendue du profil F-F' de la figure 8 est indiquée.

(1992) have divided the typical lake sediment fill into two sequences. The lower, late-glacial, ice-contact and proglacial sequence consists of inorganic mud and silt and is seismically characterized by having a parallel reflection configuration. Our Unit A corresponds to this sequence. Shilts and Clague (1992) defined an upper, acoustically transparent sequence composed of organic and mineral sediments (gytja and mud). Our Unit B corresponds to this upper sequence. Shilts and Clague (1992) pointed out that the physical characteristics, thickness and relative proportions of the two seismic stratigraphic sequences differ from lake to lake due to differences in late-glacial and postglacial history. Although not discussed in this paper, the detailed variations in Units A and B appear to reflect differences related to areas inundated (for example, Lake Simcoe and western Kewartha Lakes) and not inundated (eastern Kewartha Lakes) by glacial Lake Algonquin. The seismic section is obscured in places by the presence of sediment gas-charged at depth. If this deep gas-charging, pending future studies, proves to be characteristic of lakes floored by Paleozoic bedrock, it has collected at a deeper stratigraphic level than the gas generated at the base of Unit B in many lakes on the Canadian Shield (Edwards and Klassen, 1984; Klassen and Shilts, 1982; Shilts and Farrell, 1982).

In western Lake Simcoe and Kempenfelt Bay, sediments thicken and bear evidence of disturbance. A diapiric event apparently raised the lower part of Unit A (Figs. 6 and 7), but became dormant before deposition of late Unit A and Unit B. It is speculated that this is a late glacial feature that arose from fluid pressure due to migration of buried ice meltwater (Shilts and Farrell, 1982) or from pressure of fluids vented

through fractures in the rock below; the bedrock surface shows no vertical offset. The profile in Figures 8 and 9 reveals graben-like features in Kempenfelt Bay. The graben-like feature at the mouth of Kempenfelt Bay, shown in Figure 5, involves the acoustic basement (till?) but seismic evidence for faulting is not present.

Graben-like features in Kempenfelt Bay do suggest disturbance and local settling of Unit A deposits, possibly a result of melting of buried ice blocks (Larocque, 1985; Shilts, 1984; Shilts and Clague, 1992). Ice-block ridges, resulting from stagnant glacier wastage, are common both to the south and north of Kempenfelt Bay (Deane, 1950), and stagnant ice features were recognized in the Lindsay-Peterborough area to the east and in the Haliburton region about 50 km northeast of Lake Simcoe (Kaszycki, 1985, 1987). Thus, sediment slumping and disturbance due to ice-block melting is consistent with the generally understood mode of ice-sheet retreat in the region.

There is a possibility that basement faulting is involved in the features observed in this reconnaissance geophysical survey of the Kewartha Lakes and Lake Simcoe. These lakes lie near the conjunction of two linear trends observed in potential field data over southern Ontario. Wallach and Mohajer (1990) identified coincident linear magnetic and Bouguer gravity anomalies in the area of western Lake Ontario as the Niagara-Pickering Linear Zone (NPLZ). This lineament crosses Lake Ontario in a north-northeasterly direction and extends from the Niagara Peninsula north to Lake Simcoe. Wallach and Mohajer (1990) suggested that the NPLZ may be the southern continuation of the linear magnetic anomaly which coincides with the western limit of the Central Metasedimentary Belt (Forsyth *et al.*, 1992; Forsyth *et al.*, in press). Wallach and Mohajer (1990) also identified the Georgian Bay Linear Zone (GBLZ) on the basis of potential field evidence. A prominent set of northwest-trending aeromagnetic lineaments and associated discontinuous, linear Bouguer gravity anomalies passes from Lake Simcoe toward the northeast corner of Georgian Bay. This lineament is postulated to extend southeastward into New York State (Sanford *et al.*, 1985). Brittle structures were mapped in both Precambrian and Paleozoic rocks in Ontario; these structures parallel the trends of both the NPLZ and the GBLZ (Wallach and Mohajer, 1990). Wallach and Mohajer (1990) also suggested the distribution of earthquake epicentres implies that the GBLZ may be an active fault zone. However, the southern extension of the GBLZ is not recognized in deep seismic reflection profiles in Lake Ontario (Forsyth *et al.*, in press). The outer Kempenfelt Bay area overlies the boundary between the Fishog and Go Home lithotectonic domains in the Precambrian basement (Easton, 1992) beneath only an estimated 50-80 m of Paleozoic rock cover. Clearly, additional seismic profiles and related investigations are required to better delineate the sedimentary disturbance features and to determine whether they bear any relationship to bedrock structures.

The seismotectonic characteristics of the region of the Kewartha Lakes and Lake Simcoe, and the preliminary marine geophysical studies reported here suggest that high

quality, high-resolution images of unconsolidated sediments must be collected systematically to better define the areal extent of instability features. Analysis of such profiles, in conjunction with "groundtruth" sediment coring, may lead to determination of the age and origin of features, and may contribute to an assessment of prehistoric seismicity.

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